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Inter Comparison of two Commercially Available SODARS

Hans E. Jørgensen, Ioannis Antoniou

Risø National Laboratory, Roskilde
November 2002

Abstract: In the present work two SODARs of the phased array type are compared indirectly using the top anemometer readings from the Risoe 125m instrumented meteorology mast. The two SODARs are the AeroVironment 4000 and the Metek DSDPA.90-24.

The Risoe met tower is equipped with cup anemometers at more heights, however the comparisons in this report took place using mainly the top mounted cup anemometer in order to exclude influences from the mast and the surrounding terrain on the rest of the anemometers.

The phased array SODAR (Sound Detection And Ranging) is a remote sensing instrument designed for the measurement of the wind speed. It is based on the interaction of an emitted short sound pulse of a specific frequency with the temperature (density) fluctuations of the atmosphere. As a result the frequency of the backscattered signal is changed. By emitting three sound beams at different inclinations and combining them, the SODAR can produce the profile of the wind speed vector at more heights. The height and the resolution of these measurements depends on the type of the SODAR. Furthermore the SODAR's ability to mesure depends also on the atmospheric stability conditions.

Traditionally the measurement of the wind speed for wind energy purposes, e.g. for site assessment or power curve measurements, has taken place with the use of top mounted cup anemometers on met masts. The evolution of wind turbines with larger rotors and higher hub heights has made testing more expensive as the cost of met masts increases exponentially with height. Therefore SODARs have become a potentially interesting alternative for the measurement of the atmospheric wind speed in wind energy applications. In advance to their introduction though, SODARs must prove that are able to fulfill certain accuracy criteria.

The measurements have been made possible under the project with the title: "Performance and load measurements of land- and offshore placed large turbines without the use of met. masts". The Energy Board of the Danish Ministry of Environment and Energy has financed the project. The overall aim of the project is to verify whether the SODAR can be used as an alternative to the cup anemometer measurements mounted on traditional masts.

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Contents

Preface

This report presents the results of the comparison of two different commercially available phased array SODAR's with tower mounted cup anemometer data. The measurements have been made possible under the project with the title: "Performance and load measurements of land- and offshore placed large turbines without the use of met. masts". The Energy Board of the Danish Ministry of Environment and Energy has financed the project. The overall aim of project is to verify whether the SODAR can be used as an alternative to the cup anemometer measurements mounted on traditional masts.

In the present report the response of two phased array SODARs is evaluated.

1 Introduction

In the present work two SODARs of the phased array type are compared indirectly using the top anemometer readings from the Risoe 125m instrumented meteorology mast. The two SODARs are the AeroVironment 4000 and the Metek DSDPA.90-24.

The Risoe met tower is equipped with cup anemometers at more heights, however the comparisons in this report took place using mainly the top mounted cup anemometer in order to exclude influences from the mast and the surrounding terrain on the rest of the anemometers.

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The technical specifications of the two SODARs are given in appendix A

2 Principles of the SODAR

SODARs were initially developed to investigate sound propagation in the atmosphere. Later the SODARs have been extended to investigation of the spatial and temporal distribution of velocity and some thermal parameters characterizing the atmosphere.

The phased array SODAR system used in this project is a monostatic SODAR i.e. the system transmits and receives sound through a common loudspeaker array. A shield surrounds the antenna in order to suppress ambient noise.

To measure the wind speed the specific SODAR sends out a series of three sequential acoustic pulses of a certain duration length and frequency. One signal travels in the vertical direction and the other two at an angle to the vertical. In each direction the received frequency is analyzed for the Doppler shift Δf:

$$\Delta f = 2V f_0 / c \tag{1}$$

where f_0 is the frequency of the of the transmitted sound and V is the velocity of the volume in the direction of the beam transmitted that has been hit by the sound pulse, and c is the speed of sound. The factor 2 is due to the travel forth and back of the sound from the volume of interest. The SODAR combines then the velocities in each direction to obtain the velocity vector.

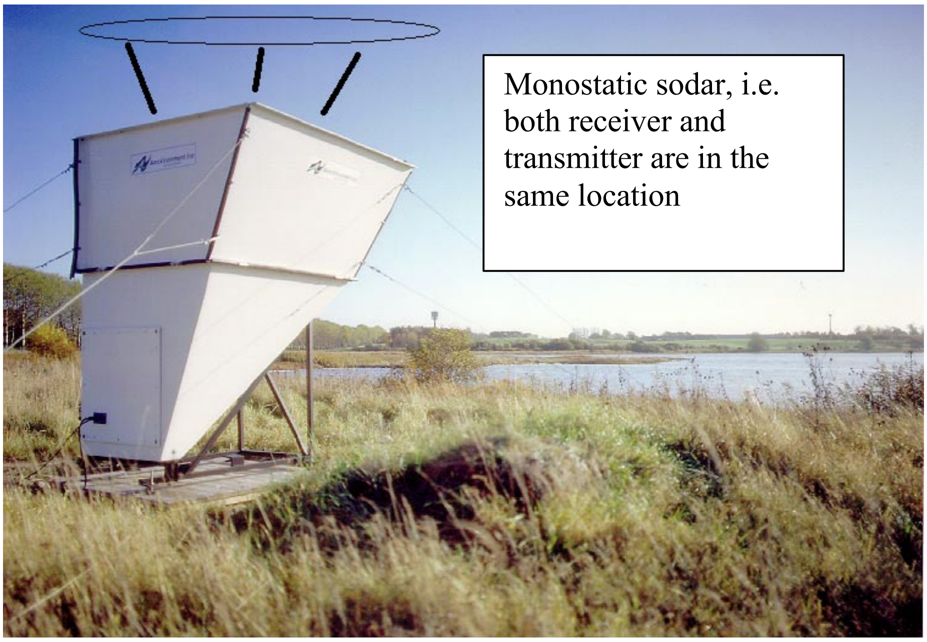

Figure 1 The Mini SODAR from Aeroenviroment. The figure illustrates that the sound beams are send out in three different directions

The scattered acoustic power that is received from the SODAR antenna at 180° relative to the emitted one is proportional to the temperature and wind speed fluctuations in the atmosphere. The scattered power per unit volume, unit incident flux and unit solid angle in dry air can be expressed as (Little 1969), Ref [1]:

$$\sigma(\theta_s) = 0.03k^{1/3}\cos^2(\theta_s)\left[\frac{C_v^2}{C_s^2}\cos^2\theta_s + 0.13\frac{C_T{}^2}{T^2}\right]\left(\sin\frac{\theta_s}{2}\right)^{-11/3} \tag{2}$$

where θ_s is the scatter angle of return (180°), κ is the wavelength, C_s the velocity of sound, T the ambient temperature, and C_T^2 and C_V^2. the temperature and velocity structure functions It is seen that the $Cos^2(\theta/2)$ is zero for 180° which thereby cancel contributions to the scattered signal from turbulence fluctuations.

2.1 Expected limitations of the SODAR

According to the international literature (Tatarsky 1971, Lenchow et al. 1986, Kristensen 1978), Ref. [2-4], the backscatter-coefficient of the sound reflected in the direction of 180 degrees, is only created by the structure coefficient of the temperature fluctuations C_T^2. In the turbulent planetary boundary layer, this coefficient is estimated as:

$$C_T^2 \approx 1.6 N \varepsilon^{-1/3} \qquad (3)$$

where N $[K^2\ s^{-1}]$ is the dissipation rate of the temperature fluctuations and ε $[m^2 s^{-3}]$ is the dissipation rate of the turbulent kinetic energy (velocity fluctuations). In the atmospheric surface layer where measurements primarily take place $\varepsilon \sim u_*^3/kz$, where z is the height above the ground, u_*^3 is the friction velocity and k is the von Karman constant.

Following equation (3), the backscatter coefficient depends on the presence of temperature fluctuations *(N)*. Thus during high wind speed situations the turbulence level can be high and thereby the value of u_* is also high. As a result C_T^2 decreases and this combined with a cloudy day with nearly no heat flux and thereby no temperature fluctuations in the atmosphere, the signal to noise levels will not be favorable for the reflected SODAR beams. This limits the ability of monostatic SODARs to measure under high wind conditions.

Two other limitations are rain and the high background noise. Both influence the signal to noise ratio levels.

3 Experimental setup

The two SODARS have been deployed near the Risø met mast for a duration of approximately six months for the Aerovironment 4000 and four months for the Metek DSDPA.90-24). The deployment took place during two different periods, respectively in the years of 1999-2000 and 2000-2001 (Table 1).

Table 1 The periods where the SODARs have been compared with the met tower

SODAR type	Start	Stop
AeroVironement	10/9-1999	20/3-2000
METEK	8/10 -2001	13/01-2002

The comparison between the cup anemometer results and the AeroVironment model 4000 is described in Ref. [5-6]. In Figure 2 toFigure 4, the surrounding terrain and the position of the two SODARs relative to the met mast is seen. The position of both SODARs relative to the met mast has been very similar during the two periods

In the case of the Metek SODAR, the depth resolution has been set to originally five meters and later to ten meters. For the AeroVironment SODAR the depth resolution was set to five meters throughout the testing period.

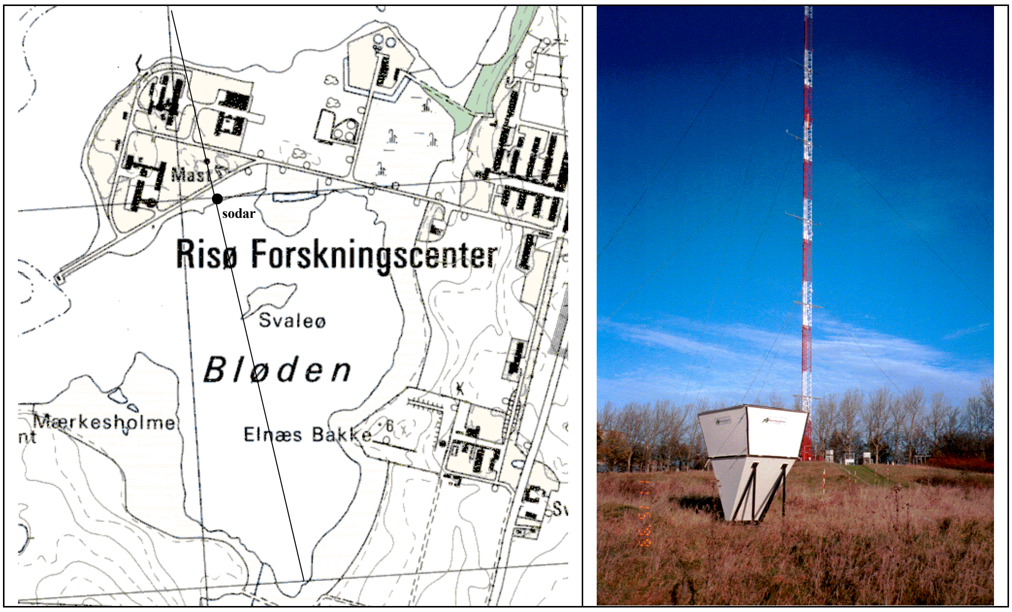

Figure 2 The location of the SODAR systems with respect to the Risø mast. The SODAR shown on the picture is the AeroVironemt model 4000. The location of the Metek SODAR was at a position 10 meter to the west of the Aerovironment SODAR

The prevailing sector for both measurement periods is shown in Figure 3, with a view taken from the METEK SODAR

Figure 3 The surroundings of the seen from the location of the Metek SODAR, (courtesy of MetSupport)

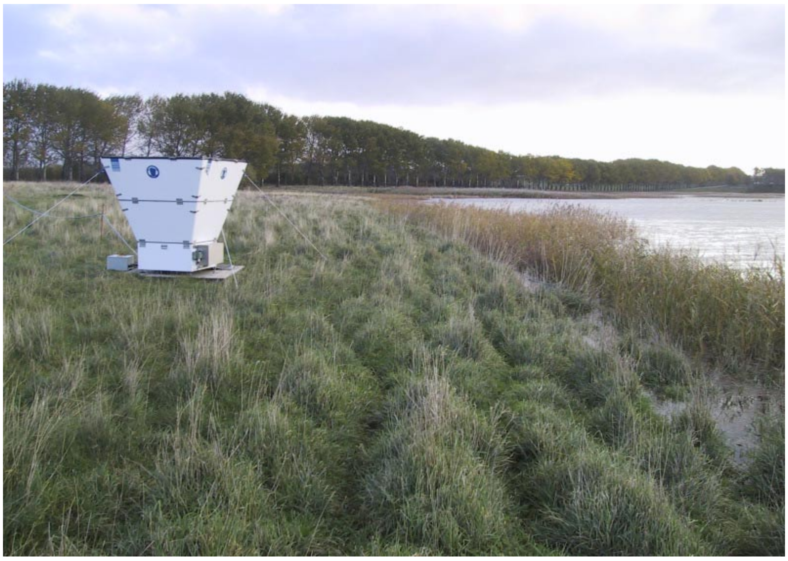

Figure 4 The Metek SODAR installed at the approximately same position as the Aerovironment SODAR. A significant noise source is shown behind the SODAR which are the 30 m high trees surrounding the Risø Alle'.

The comparisons between the AeroVironement 4000 SODAR and the met tower was unfortunately influenced by the following incidents:

1) The SODAR heat was not switch on so when snow arrived in the beginning of December the SODAR was filled with snow. Heat was then switched on.
2) The very strong December storm in 1999 with wind speeds in the order of 30 m/s tilted the SODAR.
3) The change from 1999 to 2000 caused problems in the data acquisition system of the SODAR.
4) The trucks that were cleaning the roads from snow cut the cables to the SODAR.
5) The cup anemometer on top of the mast was hit by lightning and could not be changed due to a broken elevator.

Hence a large amount of data was excluded and only data where both the SODAR and the tower signals were running, were analyzed.

During the campaign with the Metek SODAR the largest problem occurred when a time-shift of 5 min. between the SODAR and the tower from 29/08-01 to 24/10-01 due to a shift of operation parameters took place. Data in this period have therefore been excluded from the data analysis.

3.1 Meteorological conditions during the different periods

Some basic statistics of the meteorological conditions during the two measurement periods are presented below, Table 2 and Figure 5 - 7.

In general the mean values and standard deviations are of same order of magnitude whereas higher order statistics differ significant. The maximum values differ due to the very strong winter storm in December 1999. However the entire storm was not captured as the Aerovirnment SODAR was tilted due to the strong wind speeds.

Table 2 Basic statistics for the tower speed at 125 meter during the period that the two campaigns took place (only the periods where the SODARs have been running with a 5 m resolution, which was the case for the Aeronvironment SODAR all through the campaign).

	Tower speed (Aerovironment)	**Tower speed (Metek 5m)**
Mean value	9,323	10,217
Standard error	0,036	0,062
Median	9,450	10,070
Standard dev.	3,994	3,402
Kurtosis	0,697	0,045
Skewness	0,346	0,003
Minimum	0,110	0,550
Maximum	31,240	20,650
No. of measurementsl	12361	3013

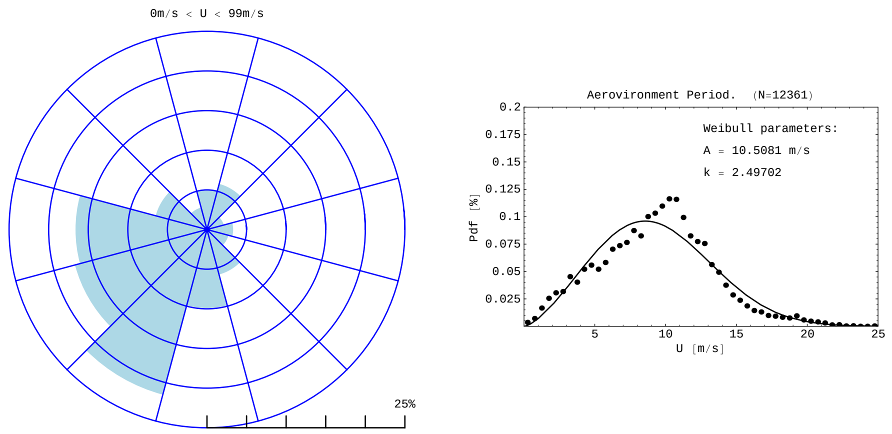

Figure 5 Frequency diagram and wind rose of the measured wind speed and direction from the tower during the period where the AeroVironment SODAR was deployed. The line is a fitted Weibull distribution to the wind data.

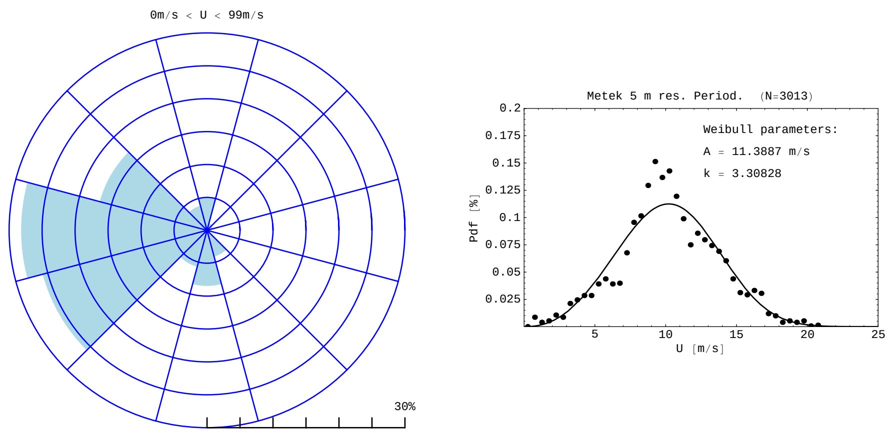

Figure 6 Frequency distribution for the period of comparison between the METEK SODAR and the met tower (5m height resolution).

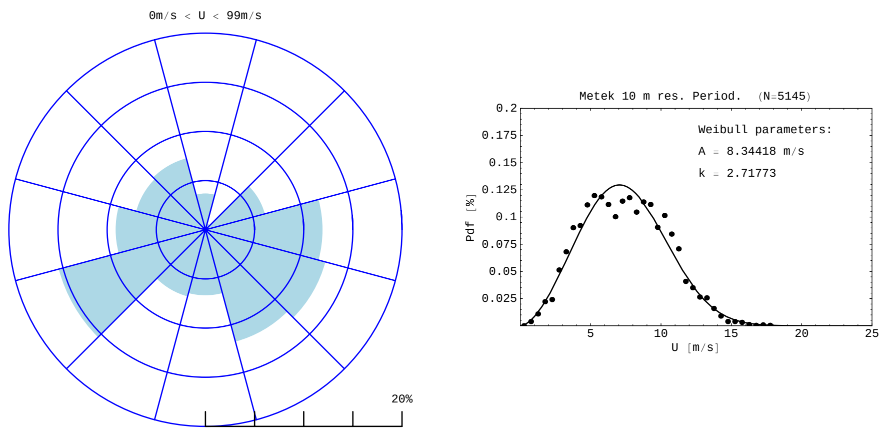

Figure 7 Frequency distribution for the period of comparison between the METEK SODAR and the met tower (10m height resolution).

4 Data analysis

In the following the data analysis from the comparisons between the SODARs and the met-tower is presented.

The main parameter, which was used for the comparison, is the signal-to-noise ratio (SNR) of the SODARs. The drawback of this choice is that the two manufacturers treat this parameter differently in their software. As we do not have knowledge of these differences in the software, the treatment of the two SODARs cannot be fully identical.

Rain weather data have been excluded a priori from the comparison.

4.1 Comparison between the Metek SODAR and the met-tower data

During the test period, the Metek SODAR has been configured using three different configurations: a 5-meter resolution, a 10-meter resolution, and a 10m resolution with a special configuration where the highest part of the shield was removed and was placed around the SODAR as an extra protection against wind noise.

In the comparison between the Metek SODAR and the met tower, the results have been screened in two different ways:

1) The effect of using the signal to noise ratio by increasing the demands on all the antennas i.e. raising the S/N ratio in steps of 1.
2) Screening by selecting only the signals that have plausibility code error less than 3 have been accepted. Metek defines this method, and for further reference the reader is advised to consult the Metek manual.

The results of the first comparison are shown in Figure 8, where the Metek SODAR data has been screened in steps of a signal to noise ratio of 1 from 5 to 9. The corresponding wind roses and pdf's for the 5 m resolution data are shown in Figure 9. The figure shows data where S/N is 5 and 9. No significant change is observed regarding the wind rose.

The decrease in resolution, Figure 8, results in the increase of the amount of the valid data sets, as a percentage of the original amount of data. For both resolutions, the correlation between the data sets of the mast and the SODAR remains almost constant with increasing SNR which confirmed the information from Metek that the SNR is not the correct filtering parameter for the Metek SODAR results.

The results of the second comparison are shown in Figure 10. Clearly of the three tested configurations the 10-meter resolution gives the best results as compared to the met tower data.

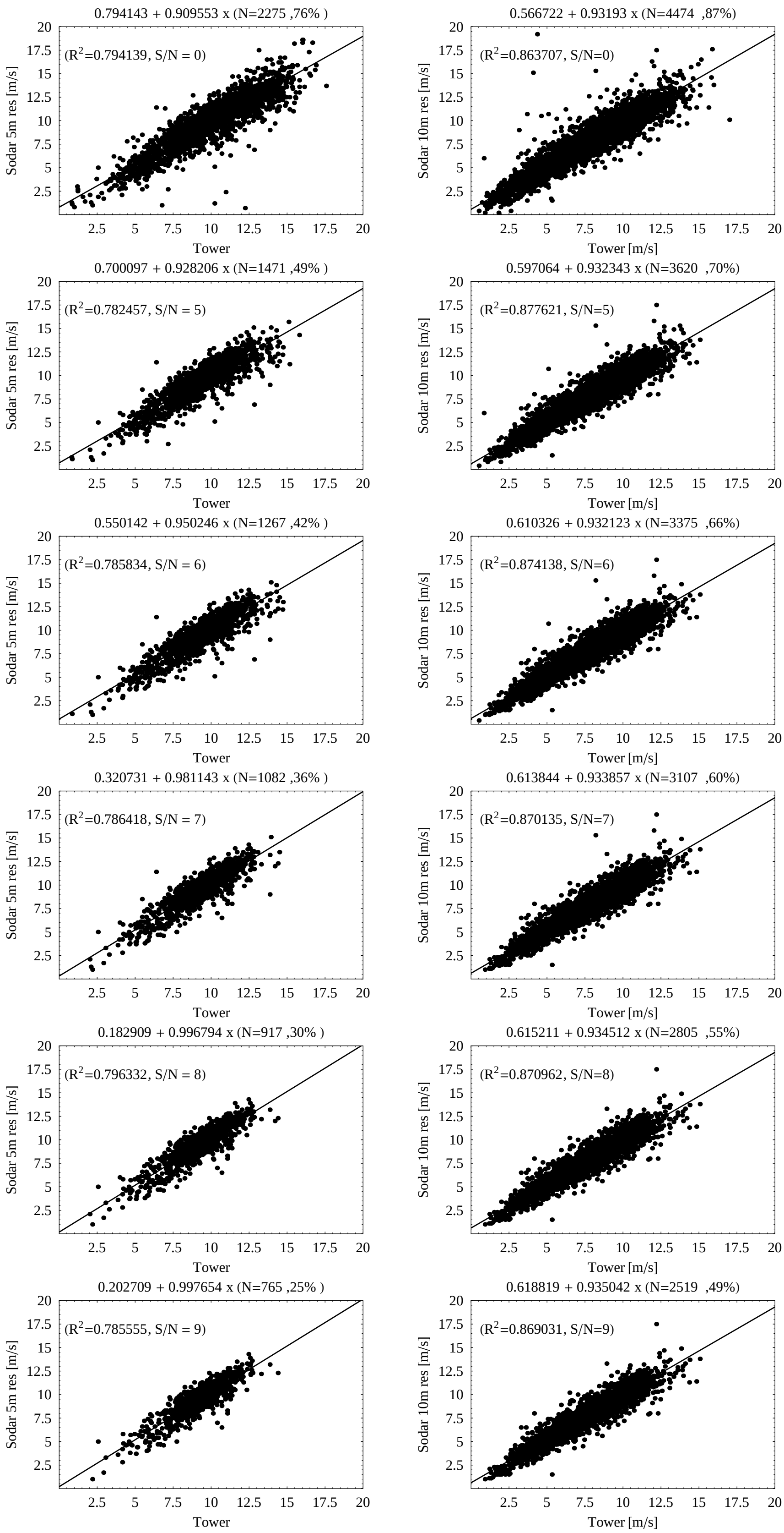

Figure 8 Comparisons between the wind speed at 125 meter (tower data) and the Metek SODAR data (left: 5m resolution, right: 10m resolution)

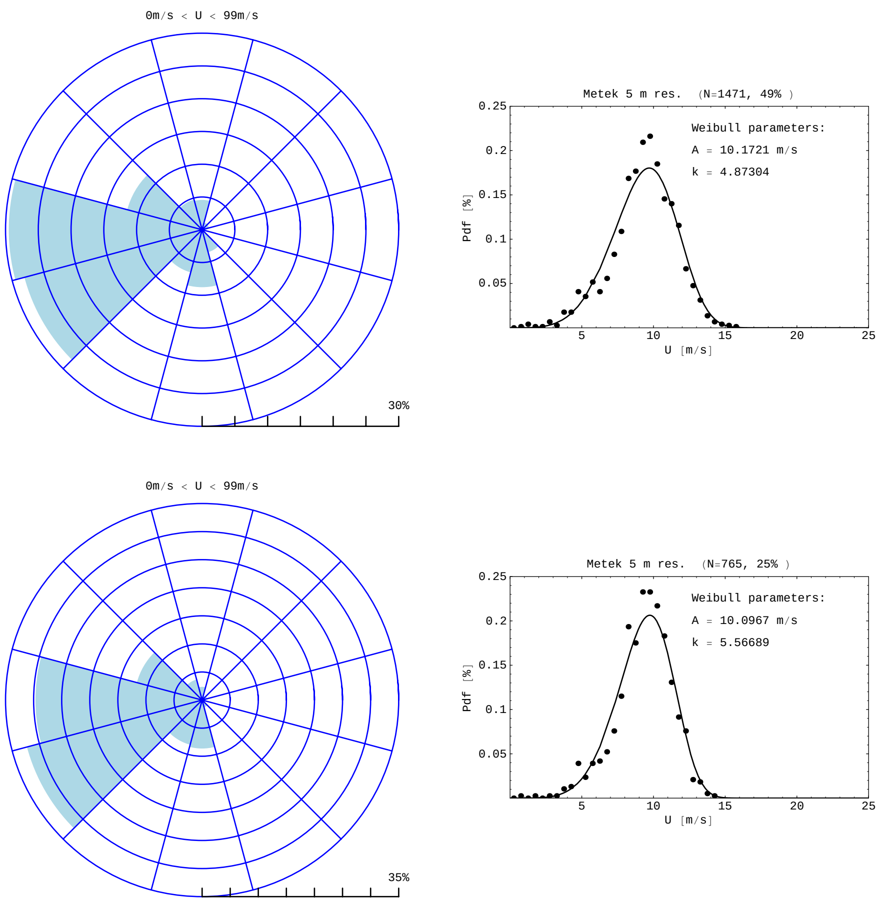

Figure 9 Wind roses and pdf's for data screened with respective a S/N of 5 and 9. The line in the pdf plot represents a fit to the tower data whereas the points are measured data by the SODAR. No significant change in the form of the pdf is present for the different filtering ratios The increased S/N ratio does not causes changes to the wind rose.

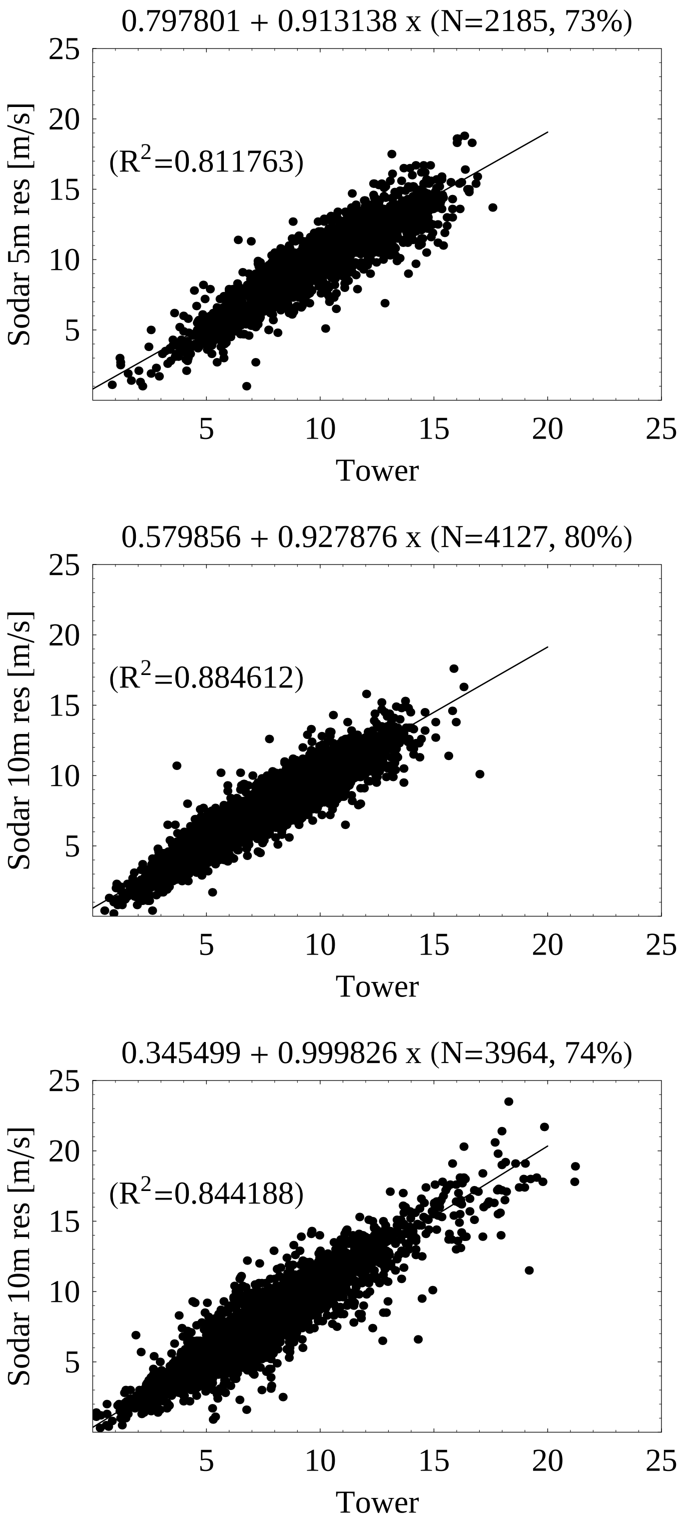

Figure 10 The comparison between the tower and the Metek SODAR when the plausibility test is fulfilled, i.e. the zero error code is smaller than 4. The comparisons are shown for the 5-meter, the 10-meter and the 10-meter resolution with noise shield configuration (from top to bottom).

Figure 11 shows a comparison of the data during the whole period i.e during both the5- and the 10-meter resolution data collected in one figure.

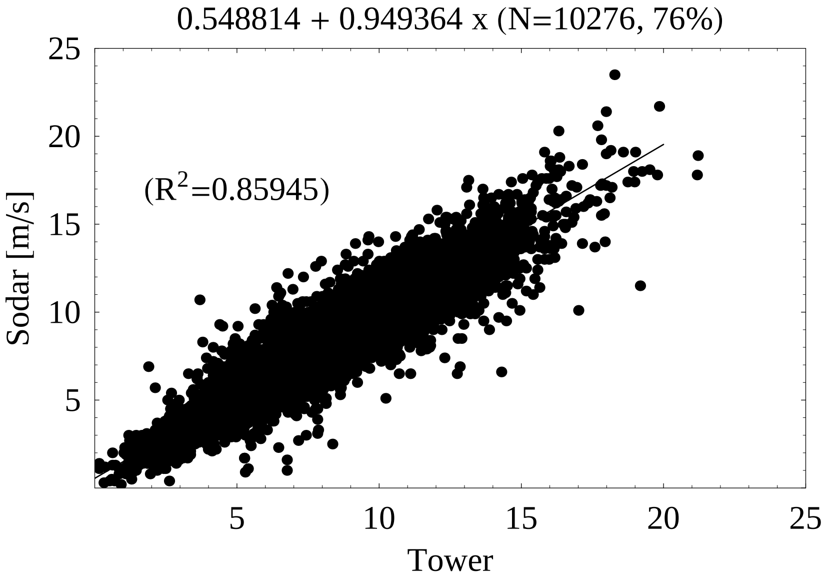

Figure 11 The comparison show is all the data shown from the period where the Metek have been measuring with the 3 different configurations.

Metek has also analyzed the data and applied their plausibility code on the data (se DSDPA.90 User Manual and Metek Graphic User Manual). The data analyzed here also includes the period where the shift of 5 minutes between the tower and SODAR data occurred, therefore the higher number of data available than in the previously shown analysis. The results give a better correlation to the tower data which however is purely coincidental.

This analysis is shown in Figure 12

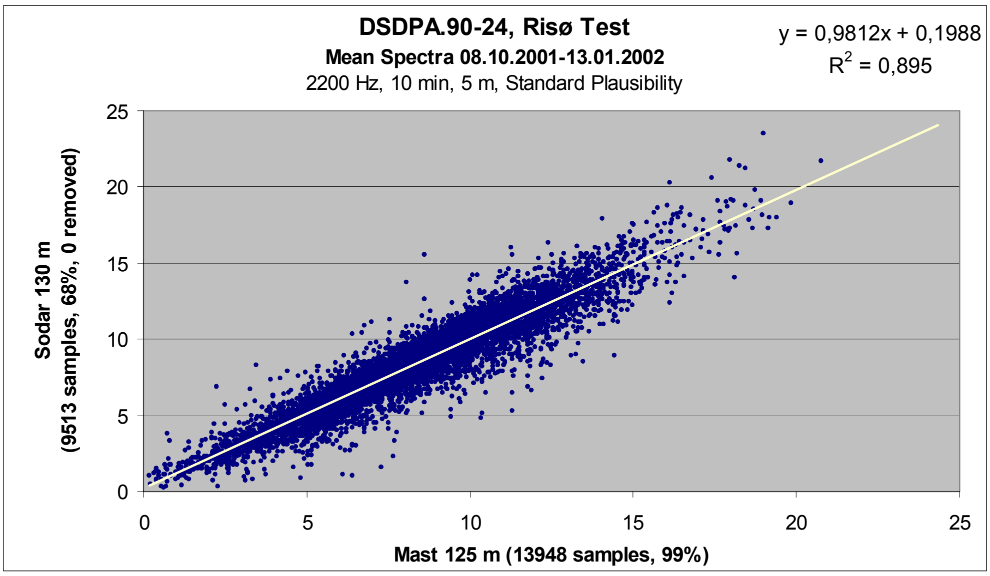

Figure 12 Data analysis performed by Hans Jurgen Kirschel from METEK with the use of the METEK data quality software.

The result shows that the screening procedures applied by Metek work slightly better than the simple procedures with S/N and error codes.

4.2 Comparison between the AeroVironment SODAR and the met-tower data.

The SODAR data have been screened in the following way:

1) The signal to noise ratio between of the SODAR has been increased in steps of 1 from 5 to 9.
2) An additional analysis has been made where these criteria have been applied for both the 130 m and 80 m level.
3) Data with abnormally large signal to noise ratios at any height (e.g. larger than 30), which are the result of fixed echoes, have been excluded.

If no filtering is applied and all available data are considered there will exist a considerable scatter in the data as shown in Figure 13. The figure shows that it is necessary to perform a filtering of the data to obtain a reasonable quality of the Aerovironment SODAR data.

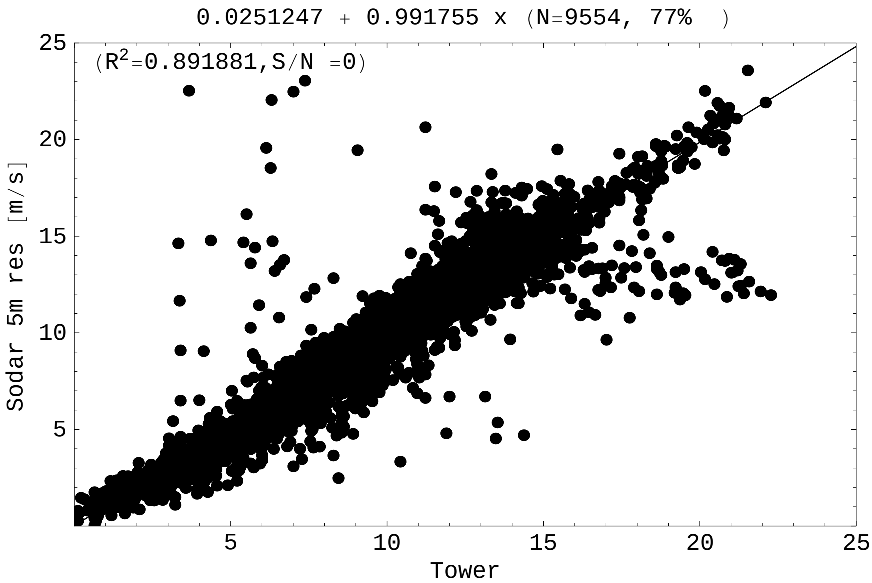

Figure 13 Comparison the SODAR to the tower with no filtering. Approximately only 80 % of the data from the whole period is available due initial factory filtering of the SODAR data.

The corresponding pdf of both the tower and the SODAR data, see Figure 14, does not look so bad in average as the one to one comparison.

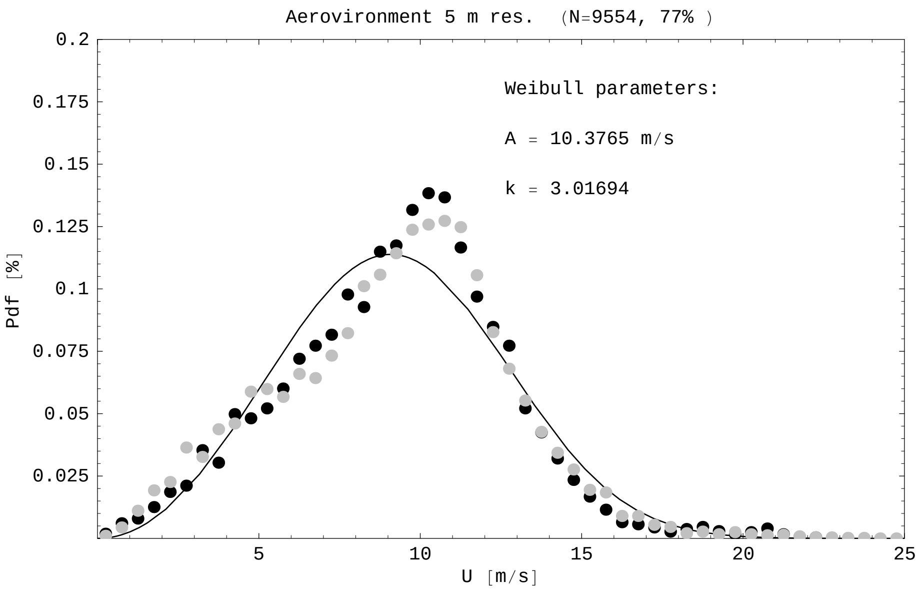

Figure 14 The corresponding pdf's for both the tower and the SODAR data. The gray points represent the histogram of the SODAR measurements. The black points represent the tower data and the line is the corresponding pdf fit to a Weibull distribution.

In Figure 15, the comparison of the data relative to the S/N ratio is shown. The rows in the figure shows an increasing S/N ratio and the columns show the filtering applied to respectively one and two levels, namely 130 m or 130 and 80m. There is no really a significant change between applying the filters at two levels rather than in one level.

Unlike the Metek results, the higher SNR values improve the quality of the correlation of the tower to the SODAR results and remove most of the data points where large differences occur between the cup anemometer and SODAR wind speed values. The demand of validity of the data at more levels does not significantly influence the quality of the results.

In order to test whether there is any direction that has a significant effect on the signal to noise ratio the wind rose of the for the two data set filtered with a S/N level of 5 and 9 have been shown with their respective pdf's, see Figure 16. No significant change is found due to directional dependency, see figure uu. The effect of filtering is here clearly shown on the tails, which are substantial reduced when we filter with a S/N ratio of 9.

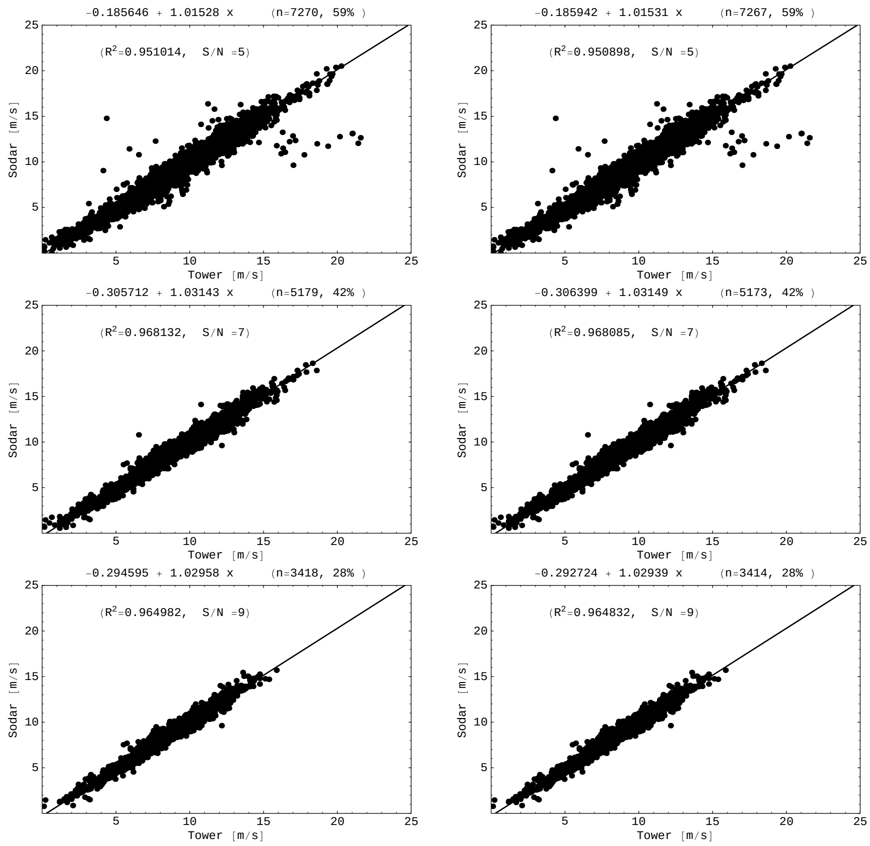

Figure 15 Comparison between the Aerovironment SODAR and the tower data where the SODAR data have been filtered according to the S/N ratio. The columns show difference between applying the S/N criteria at respectively one level (130m) and two levels (130 and 80 m) simultaneously.

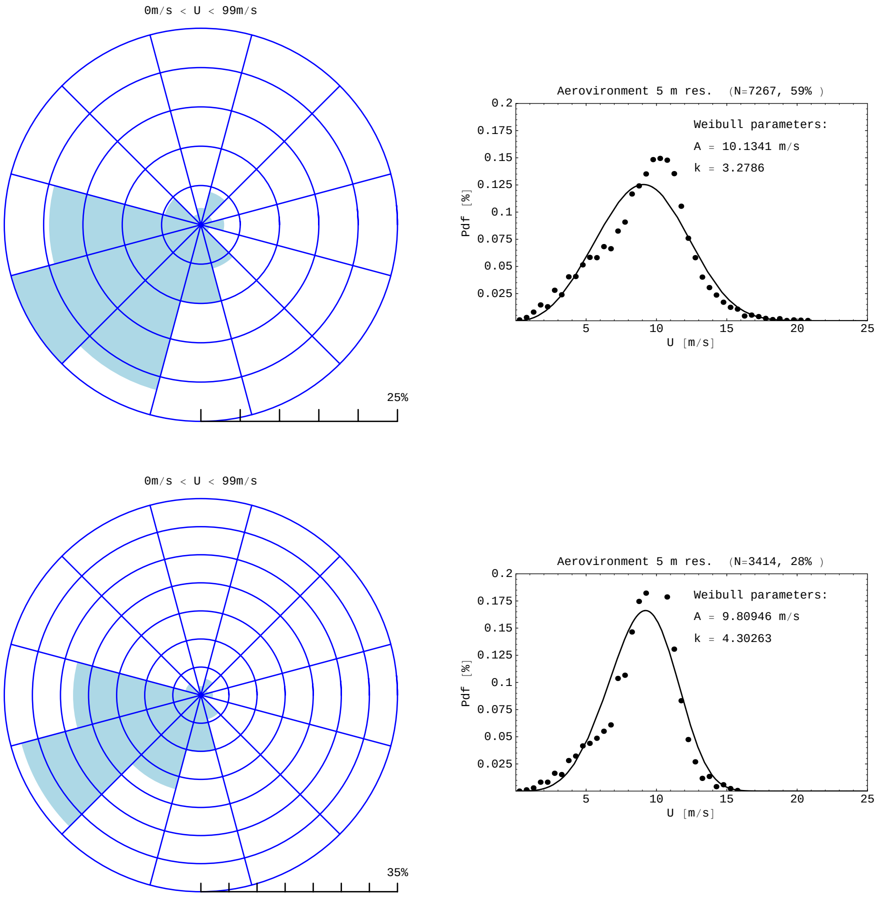

Figure 16 Windrose and pdf's for the dataset filtered with a S/N ratio of 5 and 9.

5 Summary

The overall performance of the Aeronviroment and the Metek SODAR has been investigated. Both SODARs are of the same type, yet they are different in a number of details. The two SODARs have been compared indirectly, through the met tower top anemometer results. The wind rose results show that similar wind conditions have in the average prevailed during the two test periods.

The lack of complete insight makes the comparison difficult, yet some conclusions can be drawn. Also the fact that data analysis using a 10-meter resolution did not take place for the Aerovironment SODAR, makes the comparison more incomplete.

The Aerovironment SODAR correlates better to the met tower results, compare Figure 8 and Figure 15.

The availability of both SODARs is approximately the same if the data with the 5-meter resolution are considered.

Furthermore:

1) The screening procedures are not completely identical and not completely known which mainly is due to lack of information from the Aeronvironment of how they treat their signals with regard to noise. Metek has proven to be much more open regarding their signal processing.
2) The SODARs do not operate with the same frequency; the frequency of the Aeronvironment is higher and therefore more suitable for measurements in this range.

Based on the analysis we have found that the operational characteristics of the Aeronvironment and Metek SODAR are very similar in their behavior. Using data screening, we have been to able decrease the scatter in the comparisons but with the drawback that the availability of the SODAR is reduced. This is mainly valid for the Aeronvironment SODAR, which also in this case performed better than the Metek SODAR with regard to regression and scatter.

6 Acknowledgments

The authors are grateful to the Danish Energy Agency for funding this project.

This comparison could not have been done without the very competent help from Hans Jurgen Kirschel from Metek and Poul Hummelshøj from Metsupport. Futher has Gunther Warmbier been very helpful in installing the Aeronvironment SODAR and teaching us to use it in the first steps in of the operation.

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Appendix A

Technical Specifications of DSDPA.90-24

Frequency:	**1000 ... 3000 Hz, 2200 ... 2500 Hz recommended**
Wind speed:	0 - 50 m/s
Wind direction:	0 – 360 degree
Vertical wind speed:	> +- 10 m/s
Operating temperature:	- 30 ° C to + 55 ° C (all without pos. 3) + 5 ° C to + 45 ° C (indoor components, pos. 3)
Operating humidity:	10 - 100 % (outdoor), 20 – 80 % (indoor)
Integration time:	10 seconds or more or instantaneous according to the signal repetition, increment 1 sec; for wind speed and wind direction, standard deviations of u-, v-, w-component 10 minutes or more are recommended
Number of gates:	adjustable, 1- 50
Minimum measuring height	adjustable, ≥ 15 m, increment ≥ 1m
Height resolution:	> 5 m, < 500 m, adjustable in 1 m – increments values of more than 100 m are not very informative, typical values are 10 - 30 m;
Typical measuring height	depends on atmospheric and site conditions, we define: 70 % availability (for wind speed and direction,30 m, 900 s, 50 dB stationary noise level, cluster algorithm for data evaluation): 350 m
Maximum measuring height	> 1000 m;
Transmission frequency:	adjustable within 1700 - 3000 Hz;(2200 … 2500 Hz recommended)
Signal power:	max. 800 W (elect.), automatically adjusted
Antenna gain:	typ. 20 dB, dependant on frequency
Sensitivity of receiver:	10^{-6} N/m^2, dependant on frequency
Beam width:	typ. 7 -12 °, dependant on frequency
Qualifying:	according to german DIN 3786 (11), KTA1508 (nuclear power regularity)
Power consumption:	depends on pulse repitition rate 250 W

Technical Specifications for Model 4000 MiniSODAR™ System

Maximum Altitude:	200 meters
Minimum Altitude:	15 meters
Height Resolution:	5 meters
Transmit Frequency	(approximate): 4500 Hz
Averaging Interval:	1 to 60 minutes (variable)
Wind Speed Range:	0 to 45 meters/second
Wind Speed Accuracy:	< 0.5 meters/second
Wind Direction Accuracy:	+/- 5 degrees
Weight:	255 lbs (116 kg)
Antenna Height:	4 ft (1.2 m)
Antenna Width:	4 ft (1.2 m)
Antenna Length:	5 ft (1.5 m)

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Title and authors

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23	2	16	6

Abstract (max. 2000 characters)

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Descriptors INIS/EDB

ACOUSTIC DETECTION; ANEMOMETERS; COMPARATIVE EVALUATIONS; REMOTE SENSING; VELOCITY; WIND